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13. ABSTRACT *(Maximum 200 words)*

The development of ultra-sensitive detectors and ultra-low-noise lasers for two-photon spectroscopy is described.

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TWO-PHOTON SPECTROSCOPY
BEYOND THE STANDARD QUANTUM LIMIT

Final Report

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1. Table of Contents

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3. Ultra-sensitive two-photon spectroscopy

3.1. Statement of the problem

The primary goal of our program is to measure the photon noise of a laser beam amplifed by the two-photon stimulated emisssion process [1]. The measurement will elucidate how the photon noise of the beam of light is modified due to quantum effects as it propagates through the highly nonlinear amplifier and it will address several outstanding theoretical questions concerning two-photon lasers. Since the noise properties of the beam are modified by quantum effects, the sources must generate beams of light whose noise level is at the limit set by quantum mechnaics and the detection system must be sensitive enough to discern small changes in the noise about this level. During the course of this program, we have developed an ulta-sensitive detection system needed to perform these measurements and we are currently developing diode laser sources whose noise level is at or below the standard quantum limit. The spectrum analyzer purchased with the funds from this grant is a crucial component of the detection system. In addition, it is a general laboratory instrument that is used to characterize the various sub-assemblies of the source and other electronic devices used in separate programs sponsored by the U.S. Army Research Office.

One issue that arises when performing measurements at or below the standard quatum limit is calibration of the noise level. Saturation of the photodiode or amplifiers and the frequency-dependent response of the system can easily lead to spurious results. The problems of saturation is especially important for our application because the two-photon amplifier requires a powerful laser beam to efficiently induce the stimulated emission process. One goal of our program is to implement various schemes to calibrate the absolute noise level of our detection system and the noise of the beams.

An equally important issue is developing a source whose noise level is at the standard quantum limit. In theory, any laser should operate at this level; however, environmental factors usually increase the noise level ('technical' or 'excess' noise). One method for obtaining beams that have reduced technical noise is to attenuate a noisy laser beam; another method is to use feedback techniques that stabilize the intensity of the laser [2]. We are currently pursing both of these approaches.

3.2. Summary of important results

We have developed detectors and sources for performing nonlinear spectroscopy at or below the standard quantum limit [3] in the visible and near infrared part of the spectrum. The detection system consists of high-quantum efficiency photodiodes, ultra-low-noise amplifiers, and the spectrum analyzer purchased through this grant. The source consists of a grating-fedback diode laser. An important aspect of our program is developing general techniques for calibrating and identifying the sources of noise in the systems.

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3.2.1. Detection System

The design of an ultra-low-noise detection system is governed by the requirements of the experiment and the types of noises that will be encountered in the measurement. For our application, the detector must have the ability to measure the noise of a laser beam with power in the range of ≈ 1 to ≈ 40 mW in a ≈ 10 kHz to ≈ 100 MHz bandwidth around 770 nm. The fundamental source of noise in the beam is photon fluctuation noise arises from the random arrival time of photons at the detector (also known as shot noise).[1] Additional sources of noise include: technical noise in the beam due environmental factors such as mechnical vibrations and power fluctuations, for example; correlations imposed on the beam due to the quantum nature of the two-photon amplification process; and electronic noise in the detector, amplifier, and resistors.

The standard approach for measuring amplitude noise in laser beams is to use a balanced homodyne detector [2], [4] shown in Fig. 3.1 because it is straightforward to calibrate the shot noise level. The shot noise level is determined by measuring the noise spectral density of the difference between the photocurrents since any noise that is correlated in the two beams (originating from technical or quantum sources) will be cancelled. The combined effects of shot noise and correlated noise is obtained by measuring the spectral density of the sum of the photocurrents. The advantage of this technique is that it does not require an accurate calibration of the detector response, amplifier gain or the scale of the spectrum analyzer. Unfortunately, the technique can fail if there is saturation (also known as compression) in any stage of the detector even when it occurs in a frequency band well away from the spectral region of interest. We have encountered saturation problems in measurements and hence we have endevored to develop simple calibration techniques to characterize the idividual components that make up the system.
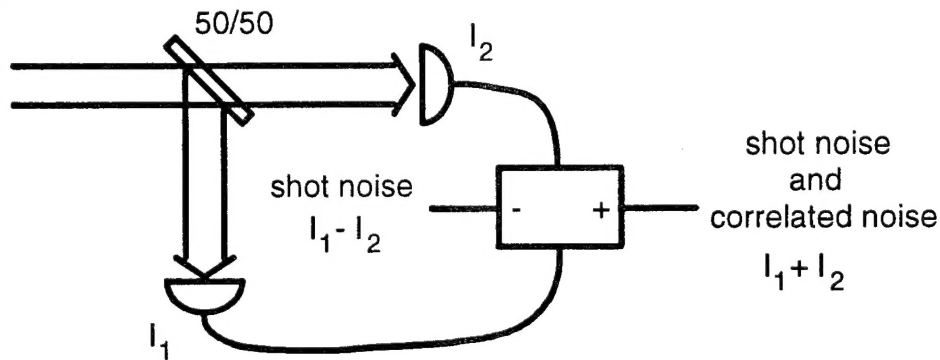

Figure 3.1: Homodyne Detector

To develop a sense for the noise levels expected in our experiment, recall that the voltage

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[1]Recall that the quantum theory of light predicts that the photon counting distribution of an ideal laser or thermal source of light obeys Poisson statisics, that is, the photons arrive a statistically uncorrelated time intervals.

noise spectral density arising from a beam of light (power P) is given by

$$V_S(\omega) \ = \ R\sqrt{2e\bar{i}\,\Delta f} \qquad [V/\sqrt{Hz}]\,, \tag{3.1}$$

where R is the resistance that converts the photocurrent to a voltage, e is the charge of an electron, and Δf is the noise bandwidth of the spectrum analyzer (typically 12% less than the resolution bandwidth for our spectrum analyzer). This noise is commonly referred to as shot noise [5]. The mean photocurrent is related to the optical power through the relation

$$\bar{i} \ = \ \frac{\eta e}{\hbar\omega}P\,,$$

where η is the detector quantum efficiency and ω is the optical frequency. The predicted shot noise level for powers in the range of 1-40 mW is equal to 0.70-4.43 $nV/\sqrt{Hz}$ at 770 nm for $R =50$ Ω and $\eta = 1$. This noise level is comparable to the other sources of noise in the system and it is comparble to the sensitivity of our spectrum analyzer. To increase the sensitivity of our detection system, we use an ultra-low-noise, flat-response, broadband amplifier to boost the signal before the spectrum analyzer.

Since one of our goals is to obtain an absolute calibration of the shot noise, we have developed convenient techniques to calibrate the detector subassemblies. We have found that the gain and noise figure of the amplifier and the response of the spectrum analyzer can be determined with reasonable accuracy ($<5\%$) by measuring the Johnson noise of a resistor. This measurement gives useful information because: the noise is white; the noise level is similar; and the response of precision resistors (e.g., metal film) closely matches the ideal response. The voltage noise produced by an ideal resistor is governed by the relation

$$V_J(\omega) \ = \ \sqrt{4k_BTR\,\Delta f} \qquad [V/\sqrt{Hz}]\,, \tag{3.2}$$

where k_B is Boltzman's constant, and T is the temperture of the resisitor. As a point of reference, the Johnson noise produced by a 50 Ω resistor at room temperture is equal to 0.91 $nV/\sqrt{Hz}$.

Only a fraction of the Johnson noise will be coupled into the amplifier since input impedance (Z) of the spectrum analyzer and the preamplifier is 50 Ω. Taking into accout the input impedance of the amplifier, the noise spectral density measured at the spectrum analyzer is given by

$$V_R(\omega) \ = \ 1.13\,G\,\sqrt{V_J^2\left(\frac{Z}{R+Z}\right)^2 + (V_{IN}^A)^2 + (V_{IN}^{SA})^2} \qquad [V/\sqrt{Hz}]\,, \tag{3.3}$$

where G (V_{IN}^A) is the gain (input voltage noise) of the amplifier, V_{IN}^{SA} is the input voltage noise of the spectrum analyzer, and the factor of 1.13 accounts for the fact that a Gaussian filter function is used in the spectrum analyzer rather than a square filter function. We find excellent agreement between the predictions of Eq. 3.3 and the experimentally measured values as seen in Fig. 3.2. Note that for $R \to 0$ or $R \to \infty$, Eq. 3.3 reduces to $V(\omega) = 1.13\,G\,V_{IN}$ and that the noise level is maximize near $R = 50$ Ω. Therefore, the gain of the amplifier and the input voltage noise can be determined by performing two noise measurements: one at $R =0$ and the other at $R = 50$ Ω. Using this procedure, we find that

$G = 1240$ and $V_{IN} = 0.36 \; nV/\sqrt{Hz}$ (corresponding to a noise figure of 0.7 dB) at 10 MHz which compares well to specified nominal values of $G = 1000$ and a maximum noise figure of 1.2 dB. We use this technique to calibrate the system and check for anomolies before performing any shot-noise measurements.
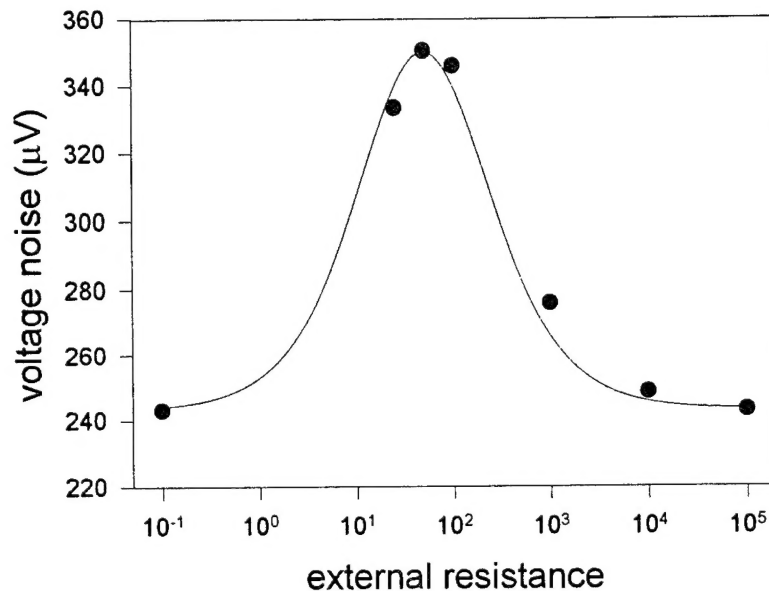

Figure 3.2: Calibration of the gain and noise level of the amplifier by measuring the Johnson noise of various external resistors. The measurement was performed at 10 MHz and $\Delta f = 250$ kHz.

Since we measure the noise properties of high-intensity beams, it is important to choose a detector that does not saturate. It has been recently pointed out that the saturation characteristics of photodiodes depend on frequency and hence the dc saturation properties cannot be used alone to evaluate the performance of detectors. We have found that the Hamamatsu S3994 (EG&G FFD 100) detector has excellent saturation characteristics [2] for dc currents in excess of 15 mA (5 mA) in the frequency range of dc-20 MHz (dc-150 MHz) with a quantum efficiency greater than 95% (80%) at 770 nm. The most accurate method for verifying to verify that the detection system is not saturated is to demonstrate that the noise spectral density of the difference in the photocurrents scales as the square-root of the power. When the technique detects nonideal behavior, it is useful to characterize the system by a different scheme to track down the sourc of the error.

As an additional check of the shot noise level, we illuminate a single detector with with a high-power light emitting diode (Hamamatsu L2168) driven by a low-current-noise power supply (see discussion below). The expected noise level measured at the spectrum analyzer

is given by

$$V_{LED}(\omega) \;=\; 1.13\, G\, \sqrt{(V_S^2 + V_J^2)\left(\frac{Z}{R+Z}\right)^2 + (V_{IN}^A)^2 + (V_{IN}^{SA})^2} \qquad [V/\sqrt{Hz}] \qquad (3.4)$$

assuming that the light emitting diode possesses no technical noise. Shown in Fig. 3.3 is the measured and predicted shot noise for $\bar{i}$=7.3 mA using the Hamamatsu S3994 photodiode. The electronic noise has been subtracted from curve and the predicted shot noise level has been scaled by the gain and bandwidth of the detection system. It is seen that there is close agreement between 1 and 20 MHz; the roll-off in the noise level above 20 MHz is due to the low-pass filter formed by the capacitance of the detector and the load resistor, and the roll-off below 1 MHz is do to the low-frequency cut-off of the amplifier..
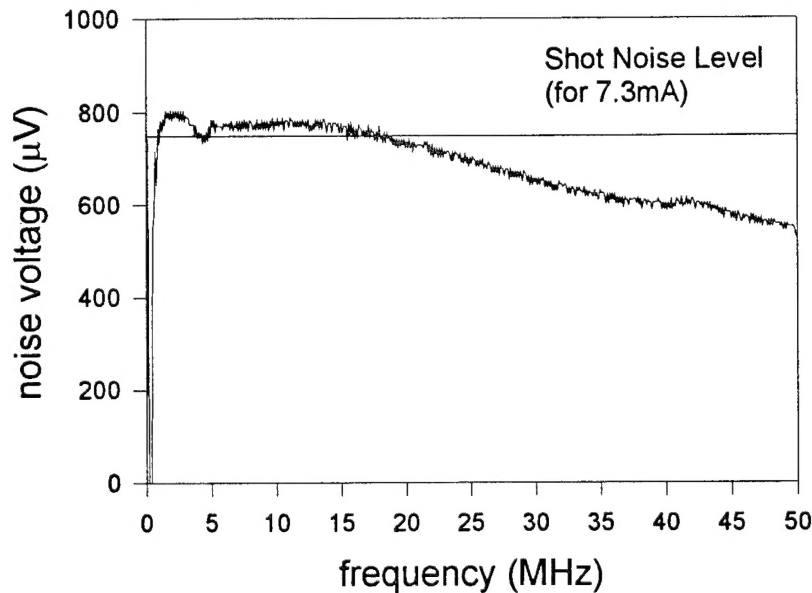

Figure 3.3: Calibration of the shot noise level using a light emitting diode. The straight line is the prediction of Eq. 3.4 assuming that the gain is frequency independent. The noise bandwidth is equal to 250 kHz.

3.2.2. Ultra-low-noise laser source

Recently, it has been shown that diode lasers at liquid helium [6] and room temperture [2] can generate amplitude squeezed light, that is, beams of light below the standard quantum limit. For this type of beam, the time interval between photons is more regular than an uncorrelated stream of photons. It is theorized that laser diodes can produce squeezed light because of several unique properties: the rate that photons are produce in the junction is highly correlated to rate at which electrons are injected into the junction because the quantum efficiency of the device is high; the quantum mechanical coupling between the

photon number and the resistance of the junction regulates the rate of injection; and it is possible to reduce the technical noise by narrowing the gain profile or using and external cavity.

Since it is important to use a current supply that has a very regular flow of electrons (stable current), we have developed an ultra-low-noise current supply that is a variation of designs developed by other researchers in atomic physics [7]. It far exceeds the best commercial devices. It can supply up to 200 mA in its present configuration (the maximum current can be increased to over 2 amps with minor modifications), it has a modulation bandwidth of $\sim$1 MHz, and the current noise is only $\sim$17 $pA/\sqrt{Hz}$ at an operating current of 70 mA. For comparison, the fluctuations in a random source of electrons with the same mean current would be 150 $pA/\sqrt{Hz}$. Hence, in principle, we could obtain nearly 20 dB of amplitude squeezing if the statistics of the photon field could reproduce the statistics of the electron source.

The detection system is used to characterize the behavior of commercial single-mode, high-power laser diodes (Spectra Diode Labs SDL-5410) driven by our low-noise current supply. We find that the lasers have significant technical noise when operated just above threshold and that this noise reduces rapidly for higher pump currents. The technical noise is attributed to beating between the single lasing mode of the laser and the spontaneous emission generated by the myriad nonlasing modes. Surprisingly, we find that the laser noise power is only a factor of $\sim$4 (6 dB) above the standard quantum limit when the laser is driven at its maximum drive current. The noise level should drop significantly using external feedback from a diffraction grating or a partial reflector. Once we have a source operating at or below the standard quantum limit, we will use it to invesitgate how the noise properties are modified by two-photon amplification and absorption processes.

3.3. List of publications and technical reports

No publications or report have resulted from this program. We intend to publish results on amplitude squeezing in diode lasers and spectroscopy of the two-photon Raman process.

3.4. List of participating personnel

No personnel were directly supported by this grant. However, the spectrum analyzer purchased by this grant is necessary for the research conducted by Mr. William Brown and Mr. David Sukow who are research assistants in Prof. Gauthier's laboratory.

4. Inventions

No inventions have been disclosed as part of this grant.

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